

UNITED STATES AIR FORCE IERA

Aircraft Corrosion Control: Assessment and Reduction of Chromate Exposures

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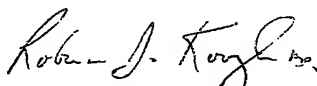
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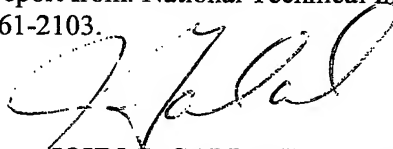
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AIRCRAFT CORROSION CONTROL: ASSESSMENT AND REDUCTION OF CHROMATE EXPOSURES

INTRODUCTION

U.S. Air Force aircraft and missiles are predominantly constructed of metallic and composite materials. The surfaces of these weapon systems are subjected to hostile environments, both natural and man-made. Inadequate control of metal corrosion or composite deterioration shortens weapon life-cycles, impacts mission accomplishment, endangers personnel, and is costly [1]. Poorly protected metallic surfaces react with oxygen in the atmosphere, resulting in oxidation of the surface; composite materials can delaminate, severely reducing the structural strength of the component. The primary means to protect against detrimental environments are coatings.

There are two main groups of coatings, namely organic and inorganic. The principal means of protection in the Air Force are organic coatings (generally referred to as "paint"). Organic coating systems provide greater protection against corrosion than an inorganic system (such as metallic plating) and are easier to maintain. An organic coating is a carbon-based semi-volatile liquid that is applied to the surface, usually through a mechanical means such as a paint spray gun. Organic coatings contain a mixture of solvents, pigments, reactants, hardeners, dryers, and corrosion inhibitors among other additives. The term "organic coatings" is usually expanded to include certain chemical surface-treatment materials that are not truly organic in nature, but are required as part of the entire organic coating system.

The coating system for metallic surfaces is a combination of pretreatment (also called a conversion coat), primer, and topcoat. The conversion coat is a chromic/nitric acid mixture that chemically reacts with the metal surface to form a chromium/aluminum complex [2]. This boundary layer is corrosion resistant and presents a surface the primer can adhere to. The primer prepares the surface for topcoat application, ensures adequate topcoat adhesion, and contains a metallic chromate that provides additional corrosion inhibition. There is no consensus among researchers on how chromates inhibit corrosion, but they do, so the Air Force uses them. The topcoat provides the final finish to the aircraft and, in some cases, provides additional stealth characteristics necessary for operational requirements.

The corrosion inhibitor of choice in the Air Force is hexavalent chromium (Cr[VI]). Cr[VI] is present in the pretreatment as chromic acid (H_2CrO_4) and in the primer as metallic chromates ($[\text{CrO}_4]^{2-}$). Worker exposures to chromate compounds can occur during application of the pretreatment and primer. Workers spray pretreatments onto metal surfaces with either pressurized hoses or hand sprayers. Primers are applied with spray guns. Aerosols generated by the spraying process can be transported into the worker's breathing zone, resulting in chromate exposures. In addition, repainting (removal of old organic coatings) and mechanical sanding of existing coating systems can release particulates that contain chromates from previously-applied primers. These particulates can also present a Cr[VI] exposure risk. Cr[VI] compounds have been linked to occupational diseases, specifically dermatitis, nasal irritation, and lung cancer [3]. Water soluble Cr[VI] compounds, such as chromic acid, are confirmed human carcinogens; metallic chromates are considered either confirmed or suspected human carcinogens, depending on the specific metal attached to the chromate [4].

Over the last three years, the Industrial Hygiene Branch of the Air Force Institute for Environment, Safety and Occupational Health Risk Analysis (AFIERA) collaborated with the Air Force Structural Maintenance community to identify improved methods to reduce Cr[VI] exposures during corrosion control procedures. We completed a series of field evaluations at Shaw, Cannon, Holloman, Nellis, Hill, Robins, Tinker, and McChord AFBs, and a chromate reduction study at Shaw and Cannon. Sampling results are in Appendices A and B. This technical report summarizes our recommended sampling

methodology, data interpretation, and chromate reduction techniques that you can use at your base to reduce chromate exposures. These techniques, along with the minimum recommended engineering controls and protective equipment requirements, will be incorporated into T.O. 1-1-8, *Application and Removal of Organic Coatings, Aerospace and Non-Aerospace Equipment* by the Air Force Corrosion Prevention and Control Office [1].

NOTE: The primary emphasis of this report is on full-aircraft surface preparation and coating application. It does not directly address depot-level aircraft depainting procedures. Refer to our earlier technical report, *Assessing Worker Exposures During Abrasive Blasting: Industrial Hygiene Field Guidance for Bioenvironmental Engineers* for information on assessing chromate exposures during depainting [5].

DESCRIPTION OF AIRCRAFT PRIMERS

Because most chromate exposures in the Air Force are related to aircraft primers, either through their application or removal, some understanding of the composition of primers and their application methods will be helpful in understanding ways of reducing chromate exposures.

Organic Coating Ingredients

Organic coatings consist of an inorganic pigment dispersed in a vehicle consisting of a binder and solvent, along with selected fillers (also called extenders) and additives [6]. The vehicle is the total liquid component of the coating. The binder is the film-forming ingredient that holds the coating together once the coating dries. The binder may be either a naturally occurring substance, such as linseed oil, or a synthetic material, referred to as a resin. Among the most common resins in use today are alkyd, epoxy, phenolic, and polyurethane. The primary function of the solvent is to dissolve the binders and provide a coating consistency suitable for application [7]. Pigments add color, cover the background, and in some cases (such as metallic chromates) provide corrosion resistance. The extenders add body to the coating, helping the pigment fill-in surface areas and adjusting the gloss of the coating. Among the common extenders in use are talc, calcium carbonate, silica, and clay. Many different additives may be added to the coating, including anti-fouling agents (to retard algae growth), biocides (to retard mildew growth), dryers, flow modifiers, UV resistance additives, and wetting agents.

In the past, organic coatings were typically classified as either varnishes, enamels, or lacquers. A varnish has no pigment, and dries first through solvent evaporation and then by resin oxidation. An enamel is a pigmented varnish. Lacquers dry solely through solvent evaporation [6]. Enamels, on the whole, are more resistant to wear and degradation than lacquers. Modern coating formulations have essentially rendered the "varnish/enamel/lacquer" classification scheme impractical, and it's falling into disuse, although you may continue to hear these terms from some of the Corrosion Control old-timers.

Air Force Primers

As mentioned earlier, the main purpose of primer application is to protect the aircraft surface from corrosion or surface deterioration. The primer provides a surface for adhesion of the topcoat and inhibits corrosion through the presence of chromates. The Air Force uses various types of primers with varying military specifications. (Note: the military specification defines the qualification requirements and engineering parameters of the product. Several manufacturers may supply a product with a particular military specification under more than one stock number.) Among these primers are: epoxy primers, water reducible epoxy primers, polyurethane primers, and lacquer primers (see Table 1). Newer primers coming into use include polysulfide primers (which actually are spray sealants even though they are called primers) and new primer-like products such as the non-chromated "tie-coat." Primers are also classified as either regular or high-solids based on their solvent content.

Epoxy primer is a two-component coating formulated specifically for its adhesion properties and resistance to chemicals, lubricants, and corrosive atmospheres. The Air Force uses it to prime exterior aircraft surfaces prior to polyurethane topcoat application, and as a stand alone primer (no overcoat) on interior surfaces and components. Water reducible epoxy primer, formulated to meet local environmental pollution regulations (specifically California Air Resources Board Rule 1124), is used in the same locations as the regular epoxy primer. Polyurethane primer, also a two-component system, is an

Table 1. Air Force Primers

Primer	Specification	Color	Chromate Type
Epoxy	MIL-P-23377	Type I- yellow	Class C - SrCrO_4
		Type II- dark green	Class N - Non- CrO_4
Water reducible epoxy	MIL-PRF-85582	Type I- yellow	Class C1 - BaCrO_4
			Class C2 - SrCrO_4
			Class N - Non- CrO_4
Polyurethane	TT-P-2760	Type I - yellow or light brown	Class C - SrCrO_4
			Class N - Non- CrO_4
Lacquer	TT-P-1757	Type T - green	ZnCrO_4
		Type Y - yellow	

alternative to the epoxy primers and exhibits greater flexibility. Because of this, it's used for high impact areas, such as leading edge slats and entire exterior surfaces on flexible cargo and bomber aircraft. Lacquer primer is a one-component system. Type Y is designed to be overcoated like the two-component systems, while Type T is a stand-alone coating on interior surfaces. Type T is not overcoated because it has poor adhesion properties.

Up until about 15 years ago, the Air Force primed its aircraft surfaces with zinc chromate (ZnCrO_4). Concern over the carcinogenic potential of this compound caused a switch to strontium chromate (SrCrO_4). Aircraft surfaces today are primed almost exclusively with strontium chromate, although there is a move afoot to switch back to zinc chromate for some of the newer aircraft coming into the inventory (such as the F-22). Because strontium chromate provides significantly better corrosion protection than zinc chromate, you can anticipate that the Air Force will continue to prime legacy systems with strontium chromate for the foreseeable future.

The most common aircraft primer currently used in the Air Force is MIL-P-23377 Type I Class C, a high-solids epoxy primer containing strontium chromate, developed to comply with low volatile organic compound (VOC) air quality regulations [1]. The base component contains an epoxy resin binder, solvents, and strontium chromate as the corrosion inhibitor. The activator component contains amines and polyamides (called hardening or curing agents), and solvents [8,9]. The epoxy resin contained within the base is a combination of monomers and oligomers of the particular epoxy compound [10]. A monomer is the single molecule or reactive compound. An oligomer is several epoxy-containing monomers reacted together. The epoxide functional group contained within the epoxy resin is very reactive because of its unstable molecular shape (see Figure 1). The amine and polyamide functional groups found in the activator are also reactive sites. When the base (containing epoxy resin) and the activating agent (containing amines and polyamides) are mixed together, the epoxide and amine/amide groups react with each other to form cross-links and chains (see Figure 2) [11]. These chains and cross-links result in the tough, flexible, adhesive and corrosion-resistant properties characteristic of epoxy primers [10,11].

Spray Application Methods

Spray application by paint spray guns is the standard for painting Air Force aircraft and parts. This method of paint application is fast and produces uniform organic coating films. The Air Force uses

Figure 1. Epoxy Primer Functional Groups

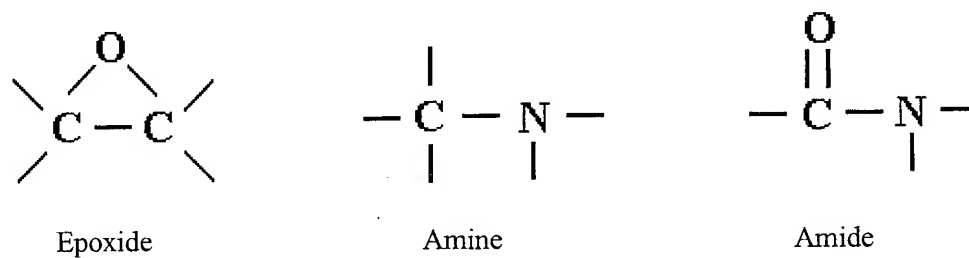
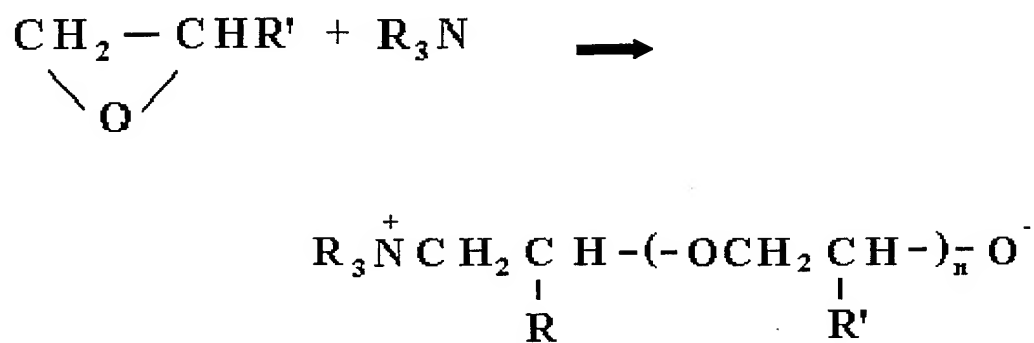


Figure 2. Reaction of Epoxide and Amine/Amide



several hand-operated spray methods, including: conventional air atomization; high volume-low pressure (HVLP) spraying; airless; air-assisted airless; and any of these methods in conjunction with electrostatics.

Conventional: In conventional spraying, the spray gun atomizes the coating by striking it with a high-speed jet of compressed air at the nozzle [12]. This atomization produces spray droplets of varying particle size that are propelled toward the surface of the weapon system by the force of compressed air. The air rebounds from the surface, forming streamlines. Droplets with sufficient inertia deviate from the streamlines and impact on the surface to form the coating. Droplets with insufficient inertia follow the streamlines and form the paint mist or overspray, which can be transported back into the worker's breathing zone [13]. Typical gun nozzle air pressures range from 50 to 65 psig, depending on the viscosity of the coating the worker sprays and the finish quality desired [14]. Paint is fed to the gun from a suction or gravity feed gun cup, or by pressure feed from a pressure pot.

HVLP: This method is similar in principle to a conventional spray gun, except it atomizes the coating by a high volume of low pressure air at the nozzle. Gun nozzle pressures are lower than a conventional gun, being less than 10 psig [14]. Because of the lower pressure, the velocity of the droplets propelled from the gun nozzle are lower and, as a result, the gun is held closer to the surface being painted. This combination of lower pressure and shorter gun-to-surface distance tends to result in a greater transfer efficiency (the fraction of the spray droplets that impact on the aircraft surface) than a conventional gun [15]. The HVLP spray gun is the most widely used spray gun in the Air Force.

Airless: An airless spray gun uses hydraulic pressure to atomize and deliver the coating. These pressures are typically on the order of 100 times that in conventional and HVLP spray guns [1]. Droplets move toward the surface by their own momentum rather than by a stream of air and are slowed down by air resistance. Because there is no compressed air to rebound from the surface, and the method produces fewer small droplets, airless spray guns tend to generate less overspray than conventional or HVLP guns [12].

Air-Assisted Airless: This method atomizes the paint with hydraulic pressure like airless spray, but at a lower pressure. Low pressure air is fed to the gun nozzle to "assist" in forming the spray pattern, allowing better control than an airless spray [1]. Air-assisted airless tends to produce better coating appearance than a purely airless system.

Electrostatics: Electrostatic spray adds electrostatic charging (up to 60,000 volts) to one of the above spray methods. The workpiece being painted is grounded, and the paint droplets are charged either inside the gun or at a metal probe at the gun nozzle. The workpiece attracts the charged droplets, improving transfer efficiency as compared to guns without electrostatics [1,12].

DESCRIPTION OF PROCESSES

Process Flow

The type of aircraft and mission of your base influences the organic coating application process.

Existing Coating Systems: At operational bases, workers typically apply organic coatings over existing coating systems in what is generally referred to as a "scuff sand and overcoat" (see Figure 3). In a scuff sand and overcoat, workers abrade the surface of the aircraft with mechanical sanders, then clean off the dust generated by the sanding procedure. Most of the original pretreatment and primer coats remain on the aircraft, so conversion coating needs to be applied only to areas where the existing coating system was removed to the bare metal. The surface is then wiped down with a solvent, primed and topcoated. The additional primer coat is not needed from a corrosion standpoint, but allows the topcoat to adhere properly. Topcoat applied directly to a scuff-sanded surface will have a limited life and can peel off, especially on fighter aircraft experiencing mach speeds. Fighter aircraft generally have their entire surface overcoated every two years or so, mainly for appearance purposes, while larger aircraft such as bombers and transports are overcoated in sections as needed. For example, wing leading edges are a high-wear area and are repainted relatively frequently at an operational base.

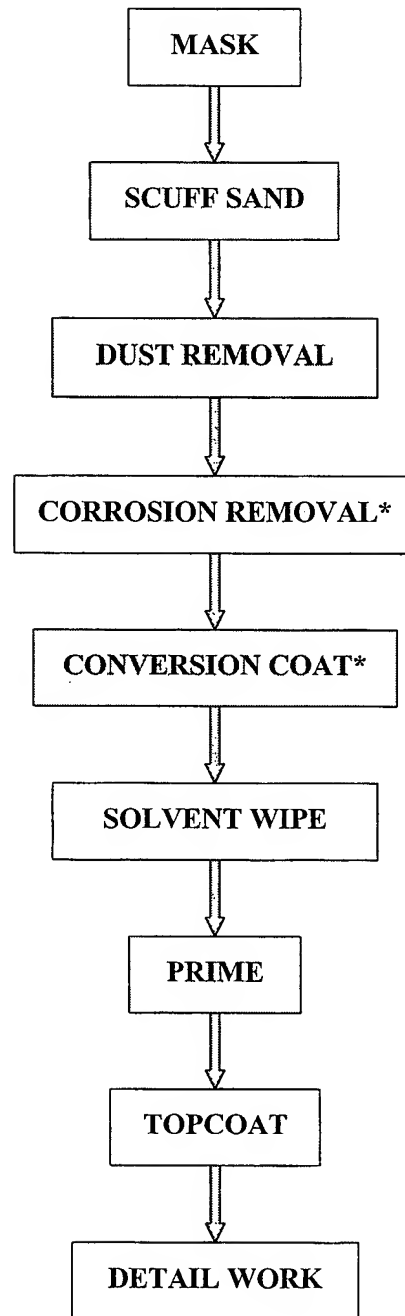
Depaint Surfaces: Every five or six years, most Air Force aircraft are sent to one of the three depots for what is known as Program Depot Maintenance (PDM). Depending on their condition, aircraft may go through either a scuff sand and overcoat or a complete depaint/paint. Depaint is the removal of all previous coating systems applied to the aircraft, through either chemical stripping or abrasive blasting and subsequent mechanical abrasion. After depaint, workers remove existing surface corrosion, then apply the conversion coating, primer, and topcoat to the surface (see Figure 4). Some aircraft, such as the B-1, are not currently being depainted at depot level but are being scuff sanded and overcoated exclusively.

Process Descriptions

Masking: Applying tape and paper to designated areas. Workers visually inspect the item and cover non-sanding areas with duct or masking tape. Masking protects interior areas from dust and abrasives. Worker exposures to chromates are not expected.

Scuff Sanding/Mechanical Abrasion: Use of motor-driven abrasives to scuff-sand and remove coatings. In scuff sanding, the workers use random orbital mechanical sanders to rough-up 100% of the painted surface, remove oxidized paint, and feather-out (blend smooth) nicked, scratched, or chipped paint. Sanders are pneumatically driven and manufactured in different size discs. Ventilated sanders have a vacuum system attached to collect generated dust particulates. The abrasive disc is normally made of aluminum oxide, and comes in different grades or grits, the coarsest being 120 grit. The grit used depends on the surface being sanded and the pressure applied by the operator. In mechanical abrasion, the worker sands the depainted surface to remove residual coatings not removed during the depaint process. For example, riveted areas are sometimes difficult to depaint through chemical means, so the workers may mechanically abrade these areas prior to applying corrosion remover. Significant worker exposures to chromate and metal-containing particulates occur during scuff sanding and mechanical abrasion.

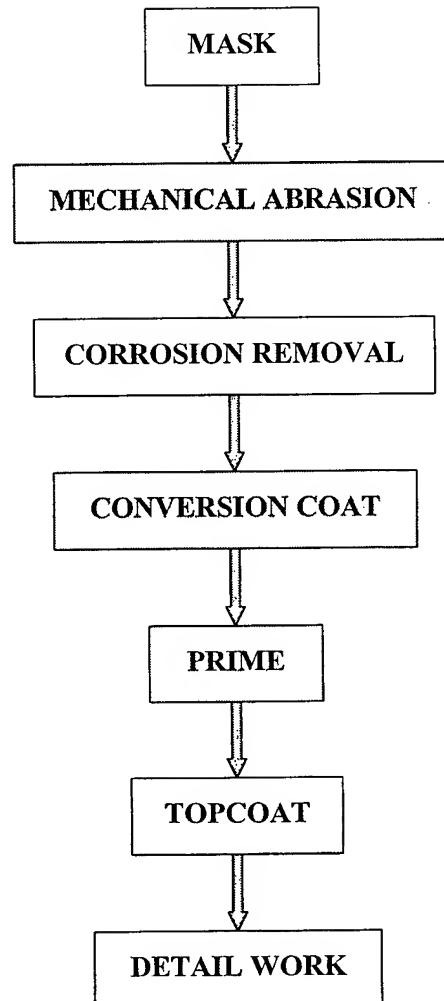
Figure 3. Process Flow: Overspray of Existing Coating System



Cr[VI] exposures

*If necessary

Figure 4. Process Flow: Coating of Depainted Surface



Cr[VI] exposures

Dust Removal: Removal of bulk dust from scuff-sanded surfaces and adjacent areas. Workers remove these dusts from the sanded surface using compressed air, hand wiping, or a high-efficiency particulate air (HEPA) vacuum. Exposures to chromate and metal-containing dusts are likely if the dust is resuspended.

Corrosion Removal: Removal of surface oxidation and corrosion products from metal alloys (also referred to as "acid etch"). Workers apply corrosion removal compound, prepaint specification MIL-C-38334, by spraying, mopping, sponging, brushing, or wiping, followed by agitation with an abrasive brush or mat. The method used depends on the amount of corrosion present on the bare metal surface. The compound contains phosphoric acid and can be an eye and skin contact hazard, but does not contain chromates.

Conversion Coating: Application of chromate conversion coating to bare metal surfaces. You will often hear the workers refer to conversion coating as "Alodine." Alodine is a trade name for a specific manufacturer's type of conversion coating. Application method depends on the amount of bare metal surface exposed. A scuff-sand and overcoat will expose only small portions of the metallic surface, so workers apply conversion coating either with a "wipe-on and blot-off" method or with a disposable applicator pen. In the wipe-on and blot-off method, workers pour liquid on a rag and wipe it onto the surface. The conversion coating reacts with the aluminum, turning it a brassy, iridescent yellowish tint. Reaction time is 3-5 minutes. Afterwards, the worker blots the area three times with a clean, water-damped rag to remove excess conversion coating. With the applicator pen (referred to as the Sempen™), the worker applies the conversion coating directly onto the surface, and rinsing is not required. Skin contact to chromic and nitric acids are the main concern with these application methods; inhalation exposures are limited. If a large area requires treatment, such as a depainted aircraft, then the worker applies conversion coating either by a fiber brush, sponge, applicator bottle, or a low-pressure stream, depending on the area and specific job requirement. As with the wipe-on and blot-off method, the aluminum will change color; workers stop the reaction by rinsing or flooding the area with clean water, which dilutes the acid component. The surface is then allowed to dry. Spraying of conversion coating can result in chromate inhalation exposures in addition to being a skin and eye contact hazard.

Solvent Wipe: Removal of residual dust and contaminants from the sanded surface prior to primer application. A clean surface is critical to ensure adequate coating adhesion. Solvent wipe is required if the surface becomes contaminated after pretreatment, after all scuff-sanding procedures, and if the primer needs to be reactivated. The Air Force uses different solvents, such as isopropyl alcohol, methyl ethyl ketone, acetone, or various mixtures. Workers use lint-free rags wetted with the solvent to wipe down the surface. There is the potential for eye, dermal, and inhalation exposure to the solvents, but chromate exposures are minimal during wipe down.

Priming: Application of primer onto either scuff-sanded or pretreated surfaces. Workers thoroughly mix the base component, usually using a mechanical shaker, and subsequently stir the catalyst into the base using a wooden paddle. The most common mix ratio for the two-component system is three parts base to one part catalyst. Manufacturers normally supply the components in kits, with the correct volume of activator for the quantity of base. To improve spray characteristics, some workers may thin a regular coating system with thinner before spraying. Workers measure primer viscosity with a Zahn Cup or a Ford Cup, which are metal or plastic cups with a small hole in the bottom [1]. The time it takes for a break to occur in the liquid flowing out of the hole is proportional to the primer's viscosity. Workers add the primer to a paint cup, a pressure pot, or a proportioning system. Epoxy primer requires a dwell (contact) time of thirty minutes so curing can begin. Workers must apply the primer before it exceeds its pot life (usually 4 hours) or it will be too viscous to spray. Inhalation exposures to components contained in the paint droplets, including chromates, epoxy resins, amines, and polyamides, are possible. In addition, volatile solvents can evaporate from the droplets into the vapor phase, resulting in additional worker exposures. Dermal exposures to primer constituents can also occur if the paint mist contacts the

worker. In addition to spray primers, there is also a disposable Sempen applicator for MIL-P-23377 epoxy primer. As with the conversion coat Sempen, inhalation and dermal exposures are minimal during use.

Topcoat Application: Application of topcoat over the primed surface. The worker must apply the topcoat before the primer completely cures, usually within 24 hours after primer application [1]. If this time is exceeded, the primer must be reactivated by a light scuff-sand and solvent wipe. Workers apply topcoats in either one- or two-coat systems, depending on the aircraft being painted. The most common types of topcoats used in the Air Force are polyurethane enamels. These enamels do not contain chromates, but do contain isocyanates, which represent their greatest health concern. For information on how to assess isocyanate exposures during polyurethane paint application, see our technical report on the subject [16].

Detail Work: Marking and identification of aircraft. These markings are either painted over the topcoated surface or overlaid with plastic film decals. Workers generally apply the markings with a detail paint spray gun, which is a smaller version of the spray guns used to paint aircraft. The paints used for detail work do not contain chromates and inhalation exposures are minimal because of the small amounts of paint used.

PARTICLE SIZE-SELECTIVE SAMPLING

Chromates generated during scuff sanding and mechanical abrasion, conversion coating spraying, and spray priming are in the form of particulates. Therefore, you need some knowledge of particulate sampling so you sample for chromates properly. Although the following information is by no means exhaustive and is in some ways simplified, it outlines the basic principles of particle size-selective sampling.

Particle Size Distributions

Scuff sanding and mechanical abrasion produces solid particles. Spraying conversion coating and primers generates liquid droplets. These particulates are not of uniform size, but can vary over a large range from less than a micrometer (μm) to greater than 100 μm [17,18]. The health risk associated with these particulates depends, besides their mass concentration, on their aerodynamic diameter. Aerodynamic diameter is the diameter of a unit density sphere that has the same settling velocity as the particle of interest. Aerodynamic diameter determines where the particles deposit in the respiratory tract, and where the particles deposit influences the subsequent development of occupational diseases [19]. Smaller particulates can reach the gas-exchange regions of the lung; larger particles tend to deposit in the upper airways and nose.

All the particulates generated during an industrial process, from the smallest to largest particulates, form a particulate mass distribution commonly referred to as the "total aerosol mass." It is impossible to accurately measure the total aerosol mass if there is a wide range of particle sizes present in the distribution you're interested in, as the collection efficiency of samplers vary for different particle sizes [20]. Therefore, in practical terms you can only accurately measure some portion of the entire distribution. There are three types of particulate distributions that are of interest from a health standpoint. The first is the "inhalable particulate mass" which is the portion of the total aerosol mass the worker would actually breathe into the respiratory tract. The second is the "thoracic particulate mass" which is the portion of the total aerosol that deposits in the lung airways and the gas-exchange regions of the respiratory tract. The final type is the "respirable particulate mass" which is the part that ends up in the gas-exchange regions of the lungs [21].

The inhalable, thoracic, and respirable mass fractions are discussed in detail in the ACGIH Threshold Limit Values (TLV[®]) Booklet, and are based on the aspiration and deposition characteristics of the human respiratory tract [4]. Although there is some disagreement on the exact number, particles with an aerodynamic diameter greater than around 10 μm are considered non-respirable. There is no consensus on an upper limit of inhalability. ACGIH criteria for the inhalable particulate mass stops at 100 μm (50% collection efficiency). You should not misinterpret this to mean only particles less than 100 μm are inhalable, although 100 μm diameter particles are considered to be towards the upper limit of what a human can inhale [22]. The TLVs for particulate exposures are generally based either on "respirable mass" or "total aerosol mass" exposures. The TLV Committee recognizes that standards based on "total aerosol mass" are unrealistic because a worker will not breathe in all of the total aerosol mass (besides being impossible to accurately measure), so particulate TLVs are changing from a total mass to an inhalable mass basis [4,23].

Chromates are associated with lung cancer, irritation of the nasopharynx and larynx, rhinitis, and perforated nasal septa [3]. This means that chromates constitute a health risk regardless of where they

deposit in the respiratory tract. Therefore, the primary distribution of interest related to chromates during corrosion control operations is the inhalable mass, and this is the distribution you need to try to measure.

Sampling Bias

It's important to realize that any sampling method for airborne particulates is biased in some way. As mentioned above, there is really no way to know the exact characteristics of the entire particle size distribution, because the very act of sampling for the aerosol will change its characteristics. For example, if you are sampling an aerosol with a high percentage of relatively large particles (higher relative mass median aerodynamic diameter, MMAD), you will underestimate the exposure when using standard 37-mm cassettes in closed-face mode. This underestimation results from the poor collection efficiency of the cassette for larger particles (i.e., the cassette has a poor aspiration efficiency for larger particles) [24]. When deciding on a sampling method, the important thing is to ensure that you do not bias your sample in a way that prevents you from making conclusions from your sampling data.

There are two sources of error when sampling from what is essentially still air: the particulate settling velocity and inertia. Bias from settling velocity occurs when the inlet to the sampling cassette is facing either upwards or downwards. If the cassette is facing upwards, the sampler will collect additional particles and cause an overestimation of the concentration. Likewise, when the cassette is facing down there is a corresponding underestimation of concentration. When the face of the cassette is horizontal there is no sampling bias from particle settling velocity [25].

Particle inertia can also introduce sampling bias. Particles follow curved streamlines that flow into the sampler inlet. As a particle approaches the inlet, its velocity will increase; if it has sufficient inertia, the particle may deviate from the streamline, causing it to be thrown away from the inlet and escaping collection. This bias depends on the size of the particle and the inlet velocity [25]. The following equation estimates the inlet diameter that produces negligible inertia sampling bias for a given particle size:

$$D_s = 0.062 Q^{1/3} d_a^{2/3} \quad (1)$$

where

D_s = sampler inlet diameter (cm)

Q = sample flow rate (cm³/sec)

d_a = aerodynamic diameter (μm)

For example, let's consider the standard 37-mm cassette. When sampling in closed-face mode, the inlet diameter is 0.4 cm. When sampling in open-face mode, the inlet diameter is 3.4 cm. At a standard flow rate of 2 liters/min (33.3 cm³/sec), by solving equation (1) for d_a we can determine at what particle size we have essentially unbiased sampling:

$$d_a = \left(\frac{D_s}{0.062 Q^{1/3}} \right)^{3/2} \quad (2)$$

$$d_a \text{ (closed face)} = \left(\frac{0.4}{0.062 (33.3)^{1/3}} \right)^{3/2} = 2.8 \mu\text{m} \quad (3)$$

$$d_a \text{ (open face)} = \left(\frac{3.4}{0.062 (33.3)^{1/3}} \right)^{3/2} = 70 \mu\text{m} \quad (4)$$

Therefore, for particles greater than about 3 μm , the closed-face cassette is biased and will not collect all of these particles. This bias will result in an underestimation of the mass concentration. The MMADs of spray aerosols are typically in the range of 15 to 20 μm [18]. This means there are a lot of particles greater than 3 μm during spraying and the bulk of the mass exposure, which is what you're interested in, is in these larger particles. Sanding procedures also generate, on a mass basis, particulate distributions much larger than 3 μm [17]. If you sample these procedures in closed-face mode, you will seriously underestimate the exposure. This might lead to incorrect decisions regarding required respiratory protection.

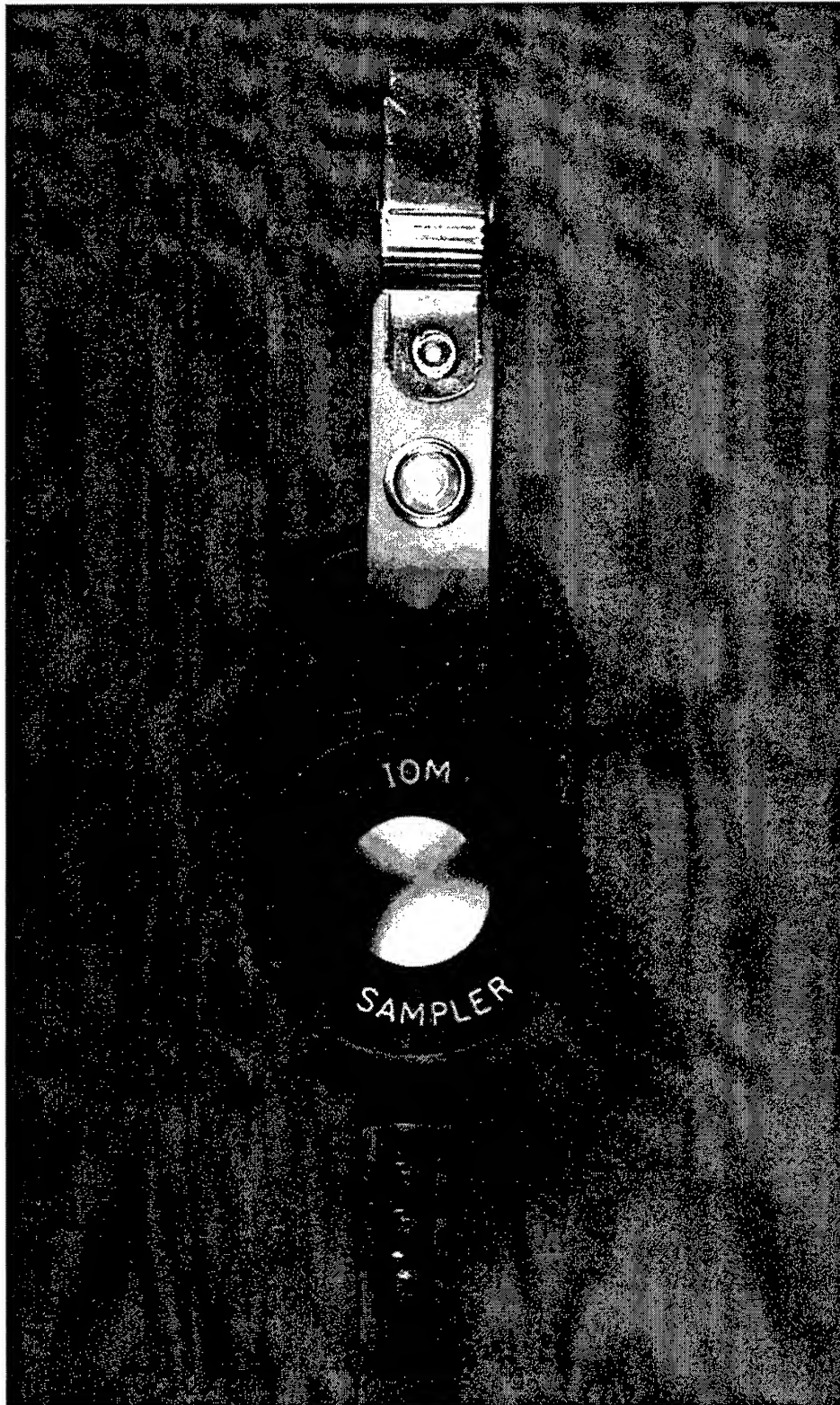
Although an open-face cassette will not experience the inertial bias problems that closed-face cassettes do (no bias for particles less than 70 μm), sampling in open-face mode can create different problems. The main problem is that when you sample in open-face mode, you'll experience deposition of the aerosol on the sides of the cassette instead of the filter. This deposition will result, again, in an underestimation of the exposure. This deposition can be significant; studies show that most of your sample can end up on the cassette walls (deposition is also a problem for closed-face sampling) [26,27]. Other problems are: the potential for damage to the filter during sampling; possible loss of collected material from the filter; and fluid flow effects that can lead to uneven deposition of the aerosol onto the filter. For these reasons, sampling in open-face mode is probably not a good idea for spraying and sanding procedures.

Inhalable Mass Sampling

From the previous discussion, it is apparent, contrary to popular belief, that so-called "total" mass samplers such as the 37-mm cassette don't actually measure total mass. 37-mm cassettes also are unsuitable for most industrial hygiene sampling of particles larger than a few micrometers [22]. Wind tunnel tests show that the 0.4-cm (closed-face) and 3.4-cm (open-face) openings do not approximate the ACGIH inhalable particulate mass curve [28]. In 1986 the Institute of Occupational Medicine in Scotland developed a sampler that closely mimics the ACGIH inhalability criteria. The sampler, called the IOM, uses a 25-mm filter contained in a cassette. The cassette has a 15-mm diameter inlet tube that protrudes 1.5 mm beyond the body of the sampler (see Figure 5) [29]. The IOM works on the principle that particulates enter the inlet and deposit either on the filter or the interior walls of the inlet tube. The sum amount of particulates in the cassette, which is the mass collected on both the filter and the inlet tube, represents the inhalable mass fraction.

If you use the IOM sampler to sample corrosion procedures, there are some limitations. For sanding procedures, you would need to send in the entire cassette to the lab for analysis, not just the filter, because

Figure 5. IOM Sampler



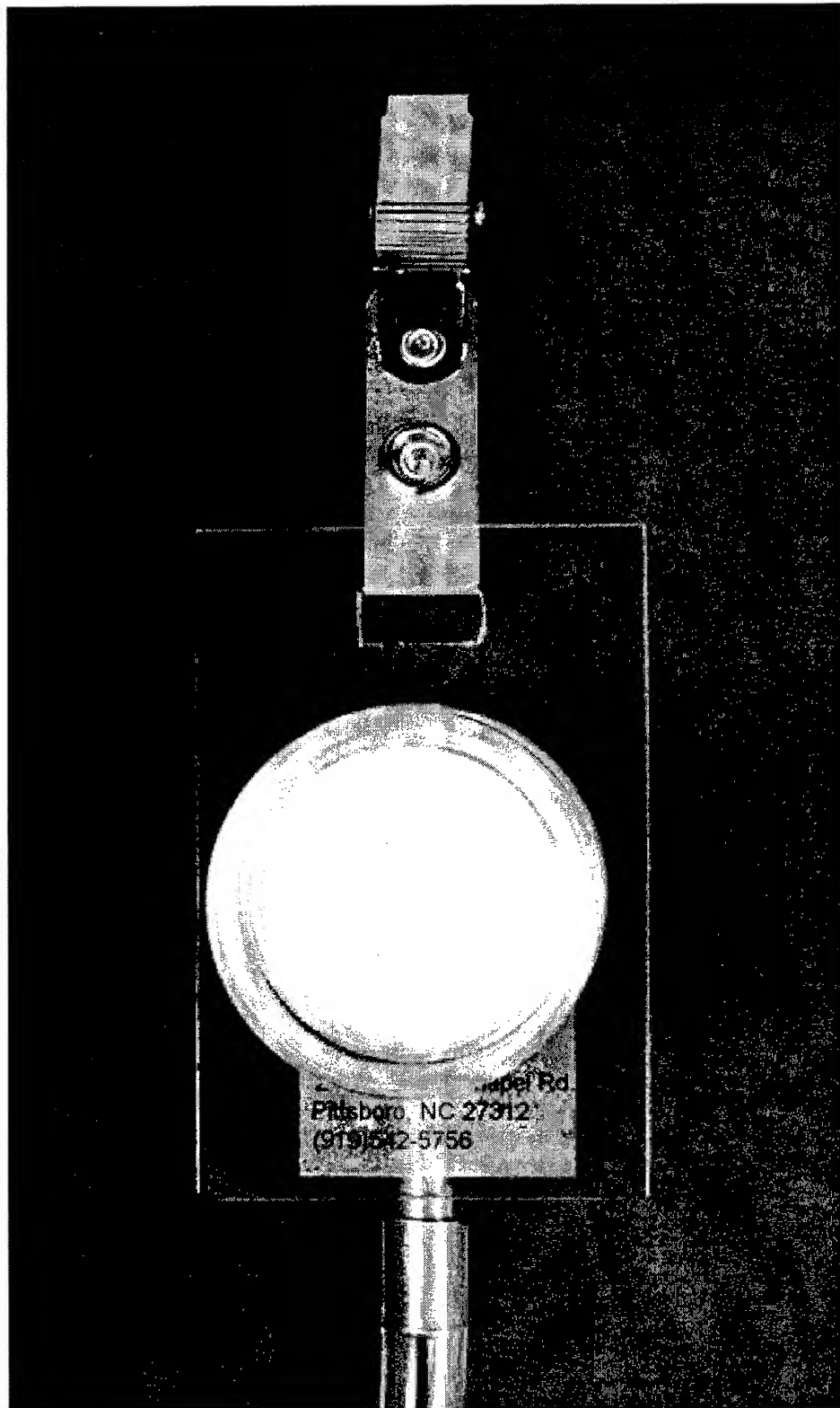
a portion of your sample is on the cassette wall. These cassettes currently cost \$13 each (June 2000), and the lab may not return them to you, so sampling could become expensive. For spray priming procedures, primer collected will adhere to the cassette wall. It's unlikely that the lab will be able to remove it for analysis. A possible solution to this problem would be to cut a 1 cm by 5 cm strip of filter and place it on the inside wall of the cassette. This filter strip will collect whatever particulates would have adhered onto the cassette wall. Analysis of the filter strip, along with the main filter, represents the inhalable mass. Cutting out strips and placing them into IOM cassettes, however, can be very time consuming and requires prior planning.

An alternative to the IOM sampler that may be practical for most Bioenvironmental Engineering shops is to use a modified 37-mm cassette. A 15-mm hole drilled in the top of the inlet cap of the cassette will mimic the collection characteristics of the IOM (see Figure 6). Collected particulates will adhere to both the sampling filter and the walls of the cassette. Side-by-side sampling of the IOM sampler and the modified 37-mm cassette indicates that the IOM (filter + inlet walls) collects, on the average, twice as much mass as the 37-mm cassette (filter only; see Appendix C). This means that 50% of the collected mass adheres to the 37-mm cassette wall and is lost and unavailable for analysis. Therefore, if you sample with the modified 37-mm cassette, you'll have to adjust for this loss using the following equation:

$$\text{Inhalable Mass} = 2.0 * (\text{37-mm cassette filter mass}) \quad (5)$$

Besides giving a better estimate of the inhalable mass exposure than either a closed- or open-face inlet opening, a 15-mm opening will also help prevent damage to and loss of material from the filter. To reduce bias from sampler orientation, use a cassette holder designed to hold the face of the cassette parallel to the worker's body (shown in Figure 6).

Figure 6. 37-mm Cassette with 15-mm Opening



AIR SAMPLING METHODOLOGY

Analytical Method

You have two analytical methods to choose from when sampling for chromates. These are NIOSH Method 7600, "Chromium, Hexavalent" [30] and OSHA Method 215, "Hexavalent Chromium in Workplace Atmospheres" [31]. Each method uses 5- μ m pore size polyvinyl chloride (PVC) filters for sampling and is specific for hexavalent chromium (Cr[VI]). NIOSH 7600 is a strict colorimetric method. After acid extraction of Cr[VI] from the sample filter, s-diphenylcarbazide (DPC) is added to the solution, which reacts specifically with Cr[VI] to form a colored complex. The solution is then read in a spectrophotometer, the absorbance being proportional to the Cr[VI] concentration. OSHA 215 is similar to NIOSH 7600, but uses an ion chromatograph to separate Cr[VI] from other analytes in the extracted sample. This separation process increases the sensitivity of the method as compared to NIOSH 7600. After ion separation, DPC is added to the solution and the concentration is read as in NIOSH 7600. OSHA 215 is said to have a limit of detection (LOD) 30 times less than that of NIOSH 7600. As of the date of this technical report, the AFIERA/Chemistry Division has the capability to perform NIOSH 7600, but cannot do OSHA 215 (they are attempting to obtain the capability). The primary disadvantage of both methods is that Cr[VI] can convert to Cr[III] if there is a long lag time between sample collection and analysis [32]. This conversion can result in an underestimation of the Cr[VI] concentration. To reduce Cr[VI] conversion, we recommend you expedite the shipment of chromate samples to your analytical lab. If Cr[VI] conversion is a significant problem, consider using the Cr[VI] Field Analytical Method. This method was designed specifically to provide analysis before Cr[VI] conversion becomes significant [33].

In the past, you may have used NIOSH Method 7300, "Elements by ICP" to analyze your chromate samples [34]. NIOSH 7300 is not specific for Cr[VI] but identifies chromium in all valence states present in your sample, including Cr[III] and chromium metal. As a result, NIOSH 7300 may overestimate Cr[VI] concentrations. In the past, the main advantage of NIOSH 7300 over NIOSH 7600 was that NIOSH 7300 had a lower LOD than Method 7600. When sampling procedures of short duration, Method 7600 may not have provided an adequate LOD for comparison with the Air Force occupational exposure limit. Analytical methods have since improved; NIOSH 7600 now has a sufficient LOD. The reported LOD for NIOSH 7600 is 0.05 μ g, which, in fact, is now lower than that for NIOSH 7300 (1.0 μ g). As a result, you should no longer use NIOSH 7300 for chromate sampling but use NIOSH 7600 instead.

Sampling Method

The best sampling method for chromates are 5.0- μ m PVC filters in 37-mm cassettes with a 15-hole drilled in the cassette cap, positioned so the face of cassette is parallel to the worker's body. Sample at a flow rate of 2.0 lpm to simulate the aspiration efficiency of an inhalable sampler.

DATA EVALUATION

Identification of Chromate Type

Cr[VI] analytical methods do not speciate among the various types of metallic chromates used on Air Force aircraft (barium, strontium, and zinc). Therefore, you need to do some sort of detective work to determine the type of chromate the worker may be exposed to. If the procedure you're interested in is priming, then the primer mil-spec will indicate the type of chromate being used. If you're sampling a sanding procedure, you will need to know the type of primer previously applied to the aircraft surface.

Strontium chromate has been the corrosion inhibitor of choice in the Air Force for the last 15 years. If the aircraft has been through depot level maintenance in the last 15 years, it's almost certain that strontium chromate primers were applied to the exterior surface. To check this, look at the Paint Facility/Finish Identification Block on the aircraft. This is a circular block, about 4 inches in diameter, located on the right side of the fuselage even with the leading edge of the horizontal stabilizer or wing (see Figure 7). It contains the date of completion and military specification of each coating system applied to the exterior of the aircraft (see T.O. 1-1-4 for details) [35]. Whenever an aircraft is scuff sanded, primed, and painted, corrosion personnel are supposed to repaint all the previous data plates. Sometimes this may not happen, however, and only the information on the last primer and topcoat are available.

If the data plates are missing, refer to the AFTO Form 95 for that specific aircraft. This form summarizes all major maintenance performed on the aircraft from the time it entered the Air Force inventory, and is supposed to contain all the information that's in the data plate. The AFTO Form 95 is usually kept in the Plans and Scheduling section of the maintenance squadron; Structural Maintenance personnel will know where the AFTO Form 95 is kept at your base. Most maintenance units have computerized their AFTO Form 95, making it relatively easy to view an aircraft's maintenance history. Aircraft sent to depot maintenance will have an abbreviated version of the AFTO Form 95 available which may or may not contain details on the coatings; the complete record is kept at the originating base.

If you have no success in finding out what type of primer is on the aircraft through either the Identification Block or the AFTO Form 95, you may be able to tell by looking at the sanded surface. There will be portions of the scuffed surface where the workers have exposed the existing primer coatings. A yellow, dark green, or light brown colored primer almost certainly contains strontium chromate as the corrosion inhibitor. A light green color probably indicates a zinc chromate primer.

Process Timelines

Sample each sanding or spraying operation separately. Sample as many workers involved in each task as possible. Make sure to record a timeline during each procedure, specifically the time the workers actually perform the procedure (task length). The task length is not necessarily the time the sampling pumps were turned on and off, since workers may take breaks or do other work during the procedure.

Exposure Calculations

Calculate both the task exposure and the 8-hr time-weighted average (TWA) exposure for the contaminants you're interested in. The task exposure is the average concentration over the length of the task, and is useful for determining effectiveness of engineering controls and respiratory protection. For

Figure 7. Paint Facility/Finish Identification Block



example, engineering controls that keep task exposures below the 8-hr TWA exposure limit will protect the worker even if an operation is performed for an entire eight-hour workday. Use the following equation to calculate the exposures if the lab reports results in mass (milligrams). If the lab reports the results in mg/m^3 and you sampled for the length of the task, the reported value is the task exposure.

$$\text{Task Exposure } [\text{mg}/\text{m}^3] = \frac{(\text{mg Cr[VI]})(10^3 \text{ lit}/\text{m}^3)}{(\text{sampling rate}[\text{lit}/\text{min}])(\text{task length}[\text{min}])} \quad (6)$$

Use the following equation to calculate the 8-hr time weighted average:

$$8\text{-hr TWA} = (\text{Task Exposure}) \left(\frac{\text{task length}[\text{min}]}{480 \text{ min}} \right) \quad (7)$$

Comparison to Exposure Standards

Occupational exposure limits (OELs) for the Cr[VI] compounds you'll most likely encounter during aircraft corrosion control are shown in Table 2 [4,36,37]. ACGIH Threshold Limit Values (TLVs), OSHA Permissible Exposure Limits (PELs), and NIOSH Recommended Exposure Limits (RELs) are shown. The ACGIH TLVs are 8-hr TWAs; the NIOSH RELs are 10-hr TWAs. The OSHA PEL is a ceiling limit. Because of this, in theory the OSHA PEL is a limit that you should never instantaneously exceed. As a practical matter, however, it is difficult to measure instantaneous levels of chromates, so if you're concerned with compliance, we recommend you compare the task exposure to the PEL. The OSHA PEL, which doesn't differentiate among the various types of metallic chromates, is defined in terms of chromium trioxide (CrO_3). CrO_3 is not a naturally occurring substance, so why OSHA decided to define its standard in this way is a mystery. The OSHA PEL of " $0.1 \text{ mg}/\text{m}^3$ of chromate as CrO_3 " corresponds to $0.05 \text{ mg}/\text{m}^3$ as Cr. Note that although the OSHA limit is a compliance limit, it was promulgated nearly 30 years ago and is out-of-date for metallic chromates. If your concern is health risk to the workers, the ACGIH TLV should be the limit you're interested in.

Table 2. Hexavalent Chromium Occupational Exposure Limits

Cr[VI] Compound	OEL (as Cr, mg/m^3)		
	ACGIH TLV (8-hr TWA)	OSHA PEL (Ceiling)	NIOSH REL (10-hr TWA)
Metallic Chromates			
Barium Chromate	0.01 ^a	0.05	--
Strontium Chromate	0.0005	0.05	0.001
Zinc Chromate	0.01	0.05	0.001
Chromic Acid	0.05 ^b	0.05	0.001

^aBased on "Insoluble Cr[VI] compounds"

^bBased on "Water-soluble Cr[VI] compounds"

The question frequently arises, if I cannot determine what type of chromate the workers are exposed to, which limit should I use? If, after reviewing AFTO Form 95s, reading the Finish Identification Block, and talking to maintenance personnel, you cannot determine what mil-spec of primer is on the aircraft, then assume it's strontium chromate primer. In the Air Force, aircraft surfaces and most aircraft parts are primed with a strontium chromate, so the odds are this is the type of primer that's been used.

Inhalable OEL vs. Existing OEL

As mentioned earlier in this technical report, ACGIH will introduce new sampling criteria based on inhalability in the near future [4]. This may lead you to ask, should I be comparing the results I obtain from inhalable sampling to the existing "total aerosol mass" OELs for chromates? The answer to this depends on the data on which the OEL was based on. For an OEL based entirely on animal or toxicological data, adjustment of the OEL is not justified since there is no occupational exposure data to reinterpret the existing OEL. If, however, the OEL was based on the results of worker personal exposures, and those exposures were measured with a so-called "total aerosol mass" sampler (such as the 37-mm cassette), then some adjustment of the OEL may be needed [38]. The current ACGIH TLV for strontium chromate is based solely on animal studies [39], so the "total aerosol mass" TLV of 0.0005 mg/m^3 will probably not be modified as an inhalable TLV. Therefore it's appropriate to compare your inhalable mass exposures directly to the current TLV. The ACGIH TLVs for zinc chromate, water-soluble and insoluble Cr[VI] compounds are based on a combination of animal and human exposure data [39], so some modification of those TLVs may be necessary. The human exposure data, however, is mostly based on sampling data from Europe, where the 37-mm cassette is not generally used, so how exactly ACGIH will adjust the current TLVs is not clear. In the interim for these substances, comparison of your inhalable sampling results directly to the current TLV is the most appropriate course of action until ACGIH decides whether or not the TLVs need adjustment.

CHROMATE CONTROL METHODS

Methods to reduce chromate exposures follow the typical control hierarchy associated with good industrial hygiene practice. Control methods for health hazards fall into four basic categories: (1) substitution, or replacing a toxic material with a less toxic one; (2) engineering controls, including process changes, isolation or enclosure of the process, and ventilation; (3) workplace practices to minimize exposures; and (4) personal protective equipment. You can use all four of these control methods to reduce chromate exposures.

Substitution

There has been considerable work among researchers and the Structural Maintenance community to identify replacements for chromated conversion coatings and primers. A few of the currently available substitutes are discussed below.

Conversion Coatings: The non-chromated conversion coating currently available is referred to as the "X-IT Precoat." This material is being used in place of chromated conversion coatings on specific aircraft at depot level. For example, Hill AFB uses X-IT Precoat on depainted A-10 and F-16 aircraft. As of the date of this technical report, however, it hasn't been approved for touch-up applications required at operational bases. Until it is, the best option is to use either the alodine Sempen or the "wipe-on and blot-off" conversion coating.

Primers: As indicated in Table 1, non-chromated primers are available for use. This does not mean, however, that they are being extensively used at the moment. There is some resistance to their use, as some item managers for specific weapon systems don't feel comfortable switching from something that's been very successful in preventing corrosion, namely chromated primers, to something else. You cannot substitute non-chromated primers for chromated primers without the authorization of the engineering authority for the weapon system or item. A different option is the so-called non-chromated "tie-coat." As mentioned earlier, from a corrosion viewpoint, the application of an epoxy primer containing chromates to a scuff-sanded surface is unnecessary as long as the original primer coat is intact. The tie-coat does not act as a corrosion inhibitor, and is not really a primer per se, but more of an adhesive. Its purpose is to bind or "tie" the polyurethane overcoat to the scuff-sanded surface, thus the name "tie-coat" [40]. You can only use the tie-coat on scuff-sanded surfaces. A depainted surface, and any portions of a scuff-sanded surface sanded to bare metal, will require application of a corrosion inhibiting primer. The tie-coat is currently authorized on certain aircraft; contact either the engineering authority or the Corrosion Prevention and Control Office (DSN 468-3284/0558, www.afcpo.com) to determine whether you can use it on your aircraft.

Engineering Controls

Ventilated Sanders: Ventilated sanders typically have a number of holes located in the rotary disc through which particulates are drawn. The sander may also have a ventilated shroud (or extractor hood) covering the disc. The sander attaches through a hose to either a vacuum containing a HEPA filter or a central vacuum system located in the shop. Ventilated sanders provide some control of sanding dusts, and worker exposures have been found to be lower when they're used, so we recommend their use [41]. They aren't nearly as effective as some manufacturers may claim, however, so buyer beware. Workers tend to modify them for their own purposes, such as removing the ventilating shroud covering the sander because

the shroud obscures their view of the aircraft surface. These modifications decrease the sanders' effectiveness.

Workers should keep the surface of the sander as flat as possible to the aircraft surface to prevent particulates from flying off the edge of the sander. Workers who use a sander with a smaller sanding disc diameter (5-inch vs. 6-inch) tend to hold the sander flatter and generate less dust. If a portable HEPA vacuum collects the dust, avoid attaching more than one sander to the HEPA vacuum and limit the hose length, since either one greatly decreases air flow to the sanders. A central vacuum system will provide a greater air flow to the sanders than a portable HEPA vacuum. Ensure the sandpaper the workers use is compatible with the sander; it should have the same number of holes as the sander and the holes should be properly aligned. Some sanders come with locking discs, while others have adhesive on the back of the sandpaper. Locking discs ensure proper alignment of the sandpaper with the holes.

Measure the air velocity at the holes and multiply by the area of the holes. If the tool has a shroud, measure velocities at several places around the shroud and multiply by the area through which the air is drawn; add this value to the air flow through the holes. Sanders should have a minimum air flow of 10 cfm per inch of disc diameter [42]. A portable HEPA vacuum will, in all likelihood, provide ventilation rates much lower than recommended; a central vacuum system, if properly operating, will probably provide better ventilation rates. Ensure the exhaust hoses are in good repair.

HEPA Vacuums: As mentioned earlier, workers may use compressed air to blow down scuff-sanded aircraft. Compressed air can resuspend the dust and create additional chromate exposures. If Corrosion personnel insist on doing this, reduce compressed air pressures to limit re-suspension of the dust. Consider using a HEPA vacuum with attachments to remove the dust from the aircraft surface. Also avoid dry sweeping the floor, which can also resuspend the particulates. It's better to HEPA vacuum the floor.

Paint Spray Guns: The transfer efficiency of a compressed air spray gun is influenced by the input air pressure and the resulting air cap pressure [18]. Proper air cap pressures will help limit excessive overspray generation. High input pressures can result in high air cap pressures, producing an overall smaller droplet size distribution of the spray. All other factors being equal, a smaller droplet size distribution will result in lower transfer efficiencies and increased exposures. Most Corrosion Control shops use HVLP spray guns to atomize the primer. As mentioned earlier, these types of spray guns atomize at lower air cap pressures than a conventional spray gun. As a result, they tend to give a larger droplet size distribution and a higher transfer efficiency than a conventional gun. This larger droplet size distribution, however, tends to produce an "orange peel" effect that is not aesthetically pleasing. Because of this, workers tend to operate these guns at air cap pressures higher than recommended, especially with high-solids coatings that are harder to aerosolize. These higher pressures increase overspray generation rates and worker exposures. It's a good idea to monitor the gun inlet and air cap pressures to ensure they're within those recommended by the manufacturer. Most manufacturers make air caps with pressure gauges attached to measure the air cap pressure. If your shop uses an electrostatic spray gun, ensure that the workpiece is grounded properly. An improperly grounded surface will actually repel charged paint droplets.

There are several makers of spray guns. Among the most common used in the Air Force are DeVilbiss, Binks, and Airverter. Workers prefer different ones for various reasons, but there is no evidence that one company's model results in overall lower chromate exposures. Worker technique and primer application rate (discussed below) tend to be the dominant factors leading to chromate exposures.

Paint Facility Ventilation: Aircraft corrosion control operations generally (but not always) occur in a ventilated facility or hangar. Ventilation systems in aircraft painting facilities can be one of three design

configurations: crossdraft, downdraft, or semi-downdraft. In crossdraft design, air enters the facility at the same elevation as it exhausts, travelling essentially in a straight line through the facility. In downdraft design, air enters through diffusers in the ceiling and exits through openings in the floor of the facility. Semi-downdraft facilities modify the downdraft design by having the air exhaust through filter banks located on one or more sides of the facility. In downdraft and semi-downdraft designs, the aircraft presents a bluff-body projection, resulting in negative pressure gradients underneath the aircraft where the workers spend considerable time during corrosion procedures. These negative pressure gradients can cause paint overspray to reverse-flow into the workers' breathing zones, increasing exposures [43]. In crossdraft design, the aircraft has a smaller signature to the air flow and negative pressure gradients are less likely to be produced in the facility, resulting in lower overall worker exposures. It is also better to position the aircraft so air flow is from the front of the aircraft to the rear, and this will result in a more streamlined flow in the facility and less air turbulence. The best facilities are designed specifically for aircraft, such as painting inserts [44]. An insert is a large spray booth designed specifically for the aircraft of interest.

It is important to remember that the primary purpose of the ventilation system is to prevent the build-up of explosive concentrations of overspray mists and vapors that evaporate from these mists. It's imperative that the facility operate under negative pressure, meaning the exhaust ducts remove more air from the facility than the supply ducts provide. This helps contain the overspray within the spray area and prevents it from migrating into adjacent office areas and uncontrolled areas where ignition sources may be present [45]. Aircraft corrosion control operations must never take place in a facility operating under positive pressure. Refer to our technical report on polyurethane paint application for information on determining appropriate paint application rates based on available ventilation [16].

Measure air velocities in the facility when empty. Measure velocities at the midpoint cross-section between the entrance and exit filters. Take sufficient measurements across this cross-section to estimate the average air flow in the facility. The average velocity should be at least 100 feet per minute (fpm) [42]. Check that the spray area is under negative pressure with a smoke tube. Release smoke at entrances to the area (such as around doors); if the smoke passes into the spray area, then the facility is under negative pressure. Smoke tubes also help identify dead spots in the facility when an aircraft is present, providing clues as to whether the ventilation system provides a uniform flow throughout the facility. Non-uniform flows indicate a system with problems, probably related to either malfunctioning fans, broken or improperly installed exhaust louvers, or clogged filters.

Workplace Practices

Primer Application Rate: Chromate exposures during priming procedures are related to excessive primer application rates (the amount of primer applied in the time it takes to prime the aircraft). At one base we visited as part of our chromate evaluations, the Corrosion Prevention and Control Office said the workers had applied three times the amount of primer required. Reduce primer application rates by either reducing the amount of primer the workers apply to the aircraft or increasing the time it takes to apply the primer.

Priming Technique: Workers' exposures during priming procedures are also greatly dependent on their technique. If possible, have only one worker at a time prime the aircraft. Workers tend to spray toward each other when more than one is spraying, contributing to elevated chromate exposures. If more than one worker must prime at a time, ensure they spray different areas of the aircraft to limit spraying each other. Workers should avoid spraying the aircraft while in the downwind position. This positioning causes the overspray to pass through the worker's breathing zone once the air flow in the facility captures it. Have the workers start priming on the end of the aircraft closest to the exhaust filters and work toward

the end closest to the air supply. This will cause the overspray to move away from the direction the workers are moving, limiting their exposure. NOTE: Aircraft cannot be overcoated in this manner as it results in a poor quality finish.

Control of Sanding Dust: AFOSH Standard 48-8 says that any area where chromates exceed the OEL must be designated a "regulated area" [46]. It's important to contain the sanding dust within the corrosion facility. The main concern is transfer of dust into administrative areas, break rooms, and other areas where personnel not directly involved in the procedure may receive incidental exposures to chromates. The ideal set-up would include a controlled entrance/exit, changing area, shower facility, and dressing area. Realizing that the ideal seldom exists in the Air Force, as a minimum designate a dedicated entrance and exit to the sanding area. Workers should remove their coveralls prior to exiting the area. Personnel not involved with the corrosion procedures should never enter the area without adequate protective equipment. AFOSH Standard 48-8 also requires the shop maintain a record or log of each entry into the regulated area.

Limiting Personnel Exposed: Keep the number of workers exposed to chromates to a minimum. Be careful when implementing individual worker time limits to reduce exposures. These time limits usually require more workers to complete the job, increasing the number of workers exposed. It's better to adequately protect, through workplace practices and personal protective equipment, fewer workers.

Personal Protective Equipment

Our minimum recommended PPE requirements for aircraft corrosion control operations are shown in Table 3 (depaint/paint) and Table 4 (scuff sand/overcoat).

Respirators: Air Force policy says that worker exposures to confirmed or suspected carcinogens (such as chromates) will be controlled to "levels that are as low as practical below the OEL or eliminated where practical" [46]. It's unrealistic to completely eliminate chromate exposures until non-chromated conversion coatings and primers replace chromated ones. Until then, the best way to keep chromate levels "as low as practical" is to ensure instantaneous concentrations the worker is exposed to *inside the respirator* be kept below the Air Force OEL. If instantaneous levels inside the respirator are below the OEL, then the worker's 8-hr TWA will never exceed the OEL. For example, suppose the chromate of interest is strontium chromate ($OEL = 0.0005 \text{ mg/m}^3$). In this case, the highest worker task exposure (the best estimate of the instantaneous level) should be 0.5 mg/m^3 if the worker wears a respirator with an assigned protection factor of 1000 (full-face airline), or 0.05 mg/m^3 if the respirator has a protection factor of 100 (full-face air-purifying) [47]. The results summarized in Appendix A indicate it's possible, through the workplace practices discussed in this technical report, to reduce task exposures during priming below 0.5 mg/m^3 and during sanding below 0.05 mg/m^3 . Chromate levels higher than these indicate the procedures are not under adequate control and actions are required to reduce the levels.

The assigned protection factor (APF) for the respirator (minimum expected workplace level of protection provided by a properly functioning respirator [47]) should be greater than the task exposure divided by the OEL. If it's not, the exposure is not "as low as practical." Either use a respirator with a larger APF or, if the task exposure divided by the OEL exceeds 1000, implement workplace practices to reduce task exposures:

$$APF \geq \frac{\text{Task Exposure}(\text{mg/m}^3)}{OEL} \quad (7)$$

Table 3: Minimum Recommended Controls and PPE for Overcoat Operations^a

Operation	Engineering Controls	Personal Protective Equipment					
		Respiratory	Hand	Ear	Eye	Body	Foot
Mask	None	None	None	None ^b	None	None	Safety toe boots
Scuff sand	HEPA-ventilated sander	Air-purifying with OV/HEPA cartridges ^c	Disposable nitrile gloves	Ear plugs	Safety goggles ^d	Tyvek or cotton coveralls	
Dust removal	HEPA vacuum			Ear plugs ^e	None		
Corrosion removal	General dilution ventilation	None		None ^b	Safety goggles or faceshield		
Conversion coat (wipe-on/blot-off)					None		
Conversion coat (Sempen)			Safety goggles or faceshield ^d		Tyvek or cotton coveralls		
Solvent wipe							
Prime/Topcoat (spray application)	Paint spray booth/facility	Air-purifying with OV/N95 cartridges ^c				None	
Prime/Topcoat (Sempen)	General dilution ventilation	None			None		

^aLocal Bioenvironmental Engineer may recommend more restrictive controls or PPE based on exposure monitoring

^bHearing protection may be required in locations where hazardous noise is produced from other sources

^cA powered air-purifying respirator (PAPR) with hood is the best choice

^dNot required if a full-facepiece or hooded respirator is worn

^eWhen noise levels exceed 85 dBA

^fWhen chemical exposure levels exceed occupational exposure limits

Table 4: Minimum Recommended Controls and PPE for Depaint/Paint Operations^a

Operation	Engineering Controls	Personal Protective Equipment				
		Respiratory	Hand	Ear	Eye	Body
Mask	None	None	None	None ^b	None	None
Mechanical abrasion	HEPA-ventilated sander	Air-purifying with OV/HEPA cartridges ^c	Disposable nitrile gloves	Ear plugs	Safety goggles ^d	Tyvek or cotton coveralls
Corrosion removal (acid etch)	General dilution ventilation	Air-purifying with HEPA filter	Butyl rubber gloves	Ear plugs ^e	Safety goggles or faceshield ^d	Rain suit
Conversion coat (alodine)		Air-purifying with OV/N95 cartridges ^c	Disposable nitrile gloves	None ^b	Safety goggles ^d	Tyvek or cotton coveralls
Prime/Topcoat	Paint spray booth/facility					Safety toe boots

^aLocal Bioenvironmental Engineer may recommend more restrictive controls or PPE based on exposure monitoring

^bHearing protection may be required in locations where hazardous noise is produced from other sources

^cA powered air-purifying respirator (PAPR) with hood is the best choice

^dNot required if a full-facepiece or hooded respirator is worn

^eWhen noise levels exceed 85 dBA

^fWhen chemical exposure levels exceed occupational exposure limits

Other Personal Protective Equipment: Workers should wear coveralls and rubber gloves to reduce skin contact with the conversion coat, sanding dust and primer. Disposable tyvek® coveralls are preferred for sanding and priming because the workers can discard them after use; reusable cotton coveralls require laundering, which can lead to exposures to laundry personnel. Workers generally prefer cotton coveralls, however, because they're cooler to wear. Recommend the use of disposable nitrile rubber gloves during sanding and spraying; they allow the workers better dexterity than either leather or reusable rubber gloves. If the workers clean their spray guns by hand with a solvent containing methyl ethyl ketone (MEK), however, disposable nitrile is not sufficient and they'll need a regular butyl rubber glove to protect their hands [48].

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APPENDIX A – FIELD SURVEY RESULTS

Survey Locations

Field studies were completed at Shaw, Cannon, Holloman, Nellis, Hill, Robins, Tinker, and McChord AFBs. The locations were chosen as representative of the types of aircraft corrosion control performed throughout the Air Force. The results from the specific bases are discussed in the individual consultative letters [49-59].

Field Study Results

Table A-1 summarizes personal exposures to hexavalent chromium during full-aircraft sanding, conversion coating application, and priming in the Air Force. Exposures are calculated as a task exposure (average concentration over the length of the task) and as an 8-hour TWA. The data was approximately lognormally distributed; means and 95% confidence limits were determined from Land's procedure for calculating exact confidence intervals around the mean of lognormally distributed data [60]. Mean task and TWA exposures exceed the Air Force OEL for strontium chromate ($0.5 \mu\text{g}/\text{m}^3$) during sanding and priming. Mean task exposures exceed the Air Force OEL for hexavalent chromium ($50 \mu\text{g}/\text{m}^3$) during conversion coat application; TWA exposures, however, are below the OEL. The data is shown graphically in Figure A-1; error bars represent 95% Upper Confidence Limits (UCL).

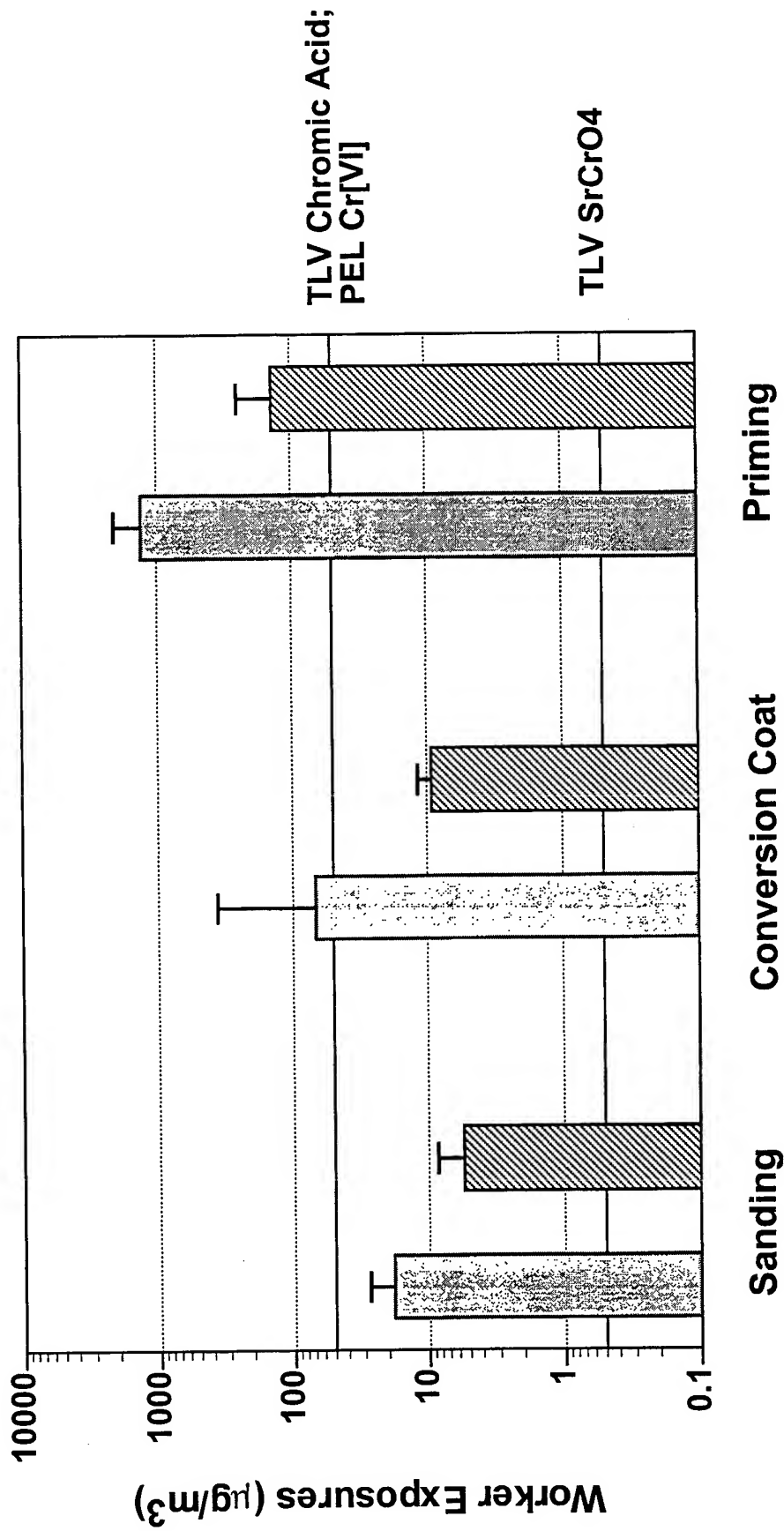
Table A-1. Cr[VI] Exposures During Aircraft Corrosion Control (Task, $\mu\text{g}/\text{m}^3$)

Procedure	Sample Number	Range	Mean	95% Confidence Limits
Sanding	97	0.26 - 100	18.3	(13.8, 27.6)
Conversion Coat	8	14.3 - 228	68.1	(37.6, 361.9)
Priming	52	9.0 - 4990	1316	(970.3, 2078)

Table A-2. Cr[VI] Exposures During Aircraft Corrosion Control (8-hr TWA, $\mu\text{g}/\text{m}^3$)

Procedure	Sample Number	Range	Mean	95% Confidence Limits
Sanding	86	0.05 - 35.9	5.51	(4.11, 8.49)
Conversion Coat	4	7.83 - 11.5	9.22	(7.78, 11.6)
Priming	50	1.0 - 458	137.0	(94.8, 248.3)

Figure A-1. Hexavalent Chromium Exposures During Aircraft Corrosion Control



APPENDIX B - CHROMATE REDUCTION STUDY

In addition to the field studies summarized in Appendix A, the Industrial Hygiene Branch of AFIERA, in collaboration with the Air Force Corrosion Prevention and Control Office, developed changes to existing practices during full-aircraft corrosion control. These new workplace practices were tested at Shaw and Cannon AFBs in order to see their impact on chromate exposures [61,62]. The emphasis during this study was aircraft scuff sanding, dust removal, and priming.

Description of Modified Procedures

In an attempt to reduce chromate exposures, several procedural modifications were evaluated. These modifications are summarized below.

Surface Preparation: Workers scuff sanded the aircraft using a DCM Clean Air Products dual action sanding unit. This unit has a 5-inch diameter circular sanding head. Collected dust passes through a hose into a high-efficiency particulate (HEPA) vacuum. Three sanding units were loaned to the IH Branch as demonstration units. Workers used 120 grit sandpaper at Shaw; they used 80 grit sand paper at Cannon. Workers were asked to focus on sanding technique such as: keeping the surface of the sander as flat as possible to the aircraft surface, reducing depth of sanding into the polyurethane topcoat, and avoiding the proximity of co-workers to the rotating sanding head

Dust Removal: After preparing the surface, workers at Shaw used the DCM HEPA vacuum unit to remove sanding dust from the aircraft. Workers removed particulates from the surface and jointed areas with two separate wand attachments. After vacuuming the aircraft surface, the workers then vacuumed the floor of the insert with the DCM unit. To complete the dust removal process, the workers wiped down the aircraft twice with a 1:1 isopropyl alcohol/water mixture. At Cannon, lack of compressed air pressure prohibited workers from using the DCM HEPA vacuum unit. Therefore, workers used compressed air to blowdown the aircraft. Workers then vacuumed the floor of the insert with the DCM unit. To complete the dust removal process, workers wiped down the aircraft with a tack rag.

Priming: After dust removal was complete, the workers primed the aircraft with a strontium chromate primer. One worker primed the top portion of the aircraft. Afterwards, a second individual primed the bottom portion. This procedure resulted in only one painter being present in the insert at a time. The workers were instructed to start priming from the end of the aircraft nearest the exhaust of the insert and work towards the air supply. This arrangement kept the painter continually moving in a direction opposite that of the paint droplet cloud. The workers were instructed to stay upwind of the area being primed and to prime with either their side or back to the direction of the airflow. Before the priming operation began, compressed air pressures at the wall, the pressure pot, and the gun air cap were checked to ensure HVLP spray gun manufacturer's recommendations were met. The workers applied a light, translucent coating of primer on the aircraft surface.

Results

Tables B-1 and B-2 show a comparison of maximum worker exposures at Shaw and Cannon AFBs before and after the modifications. Although exposures measured during sanding, priming, and painting still exceed the AF OEL, a significant reduction in measured chromate levels was obtained during each of the procedures. Specifically, chromate task exposures at Shaw were reduced 79% during sanding, 98% during dust removal, and 86% during priming. At Cannon, chromate task exposures were reduced

Table B-1. Maximum Chromate Exposures Before and After Modified Procedures
(Shaw AFB)

Corrosion Procedure	Task Exposure ($\mu\text{g}/\text{m}^3$)			8-hr TWA Exposure ($\mu\text{g}/\text{m}^3$)		
	Before	After	% Decrease	Before	After	% Decrease
Sanding	18.1	3.8	79	8.7	1.0	89
Dust Removal	245	4.1	98	12.3	0.3	98
Priming	625	86.3	86	75.5	5.6	93

Table B-2. Maximum Chromate Exposures Before and After Modified Procedures
(Cannon AFB)

Procedure	Task Exposure ($\mu\text{g}/\text{m}^3$)			8-hr TWA Exposure ($\mu\text{g}/\text{m}^3$)		
	Before	After	% Decrease	Before	After	% Decrease
Sanding Gears	100	3.79	96	5.4	0.60	89
Sanding Aircraft	31	4.50	85	7.2	0.71	90
Priming Gears	750	40.6	95	15.6	1.44	91
Priming Aircraft	842	196	77	70.2	8.58	88

85% during aircraft sanding and 77% during aircraft priming. The sanding and priming data is shown graphically in Figures B-1 and B-2.

Recommendations

This study indicates chromate exposures can be significantly reduced with relatively simple modifications. The modifications had minimal impact on aircraft turn around times, at most adding a couple of hours to the time needed to perform a complete scuff sand and overcoat. The work practice changes with the most impact for reducing exposures during each of the corrosion control operations, based upon sampling results obtained during this study, are summarized below.

Sanding: Ensure the vacuum assisted sander in use provides adequate airflow. Make sure the air hoses are in proper repair, limit the length of the hoses, and frequently remove collected dust from the HEPA vacuum units. Hold the sander flush against the work surface as often as possible. Do not sand above, below, or directly adjacent to other workers to avoid propelling dust into their breathing zone.

Dust Removal: Use HEPA vacuums to remove dust from the aircraft surface and the paint facility floor after sanding.

Priming: Only one individual should spray primer in the facility at a time. Start priming on the portion of the aircraft closest to the exhaust end of the insert and move toward the supply end. This will ensure the worker moves away from the direction of the paint droplet cloud. Workers should prime with the air flow to their side or back. Adjust compressed air pressures at the wall, pressure pot, and gun to keep air cap pressures below 10 psig for HVLP spray guns. Apply only the minimum amount of primer required onto the aircraft, producing a very translucent coating.

Figure B-1. Comparison of Chromate Exposures Before and After Modified Sanding Procedures

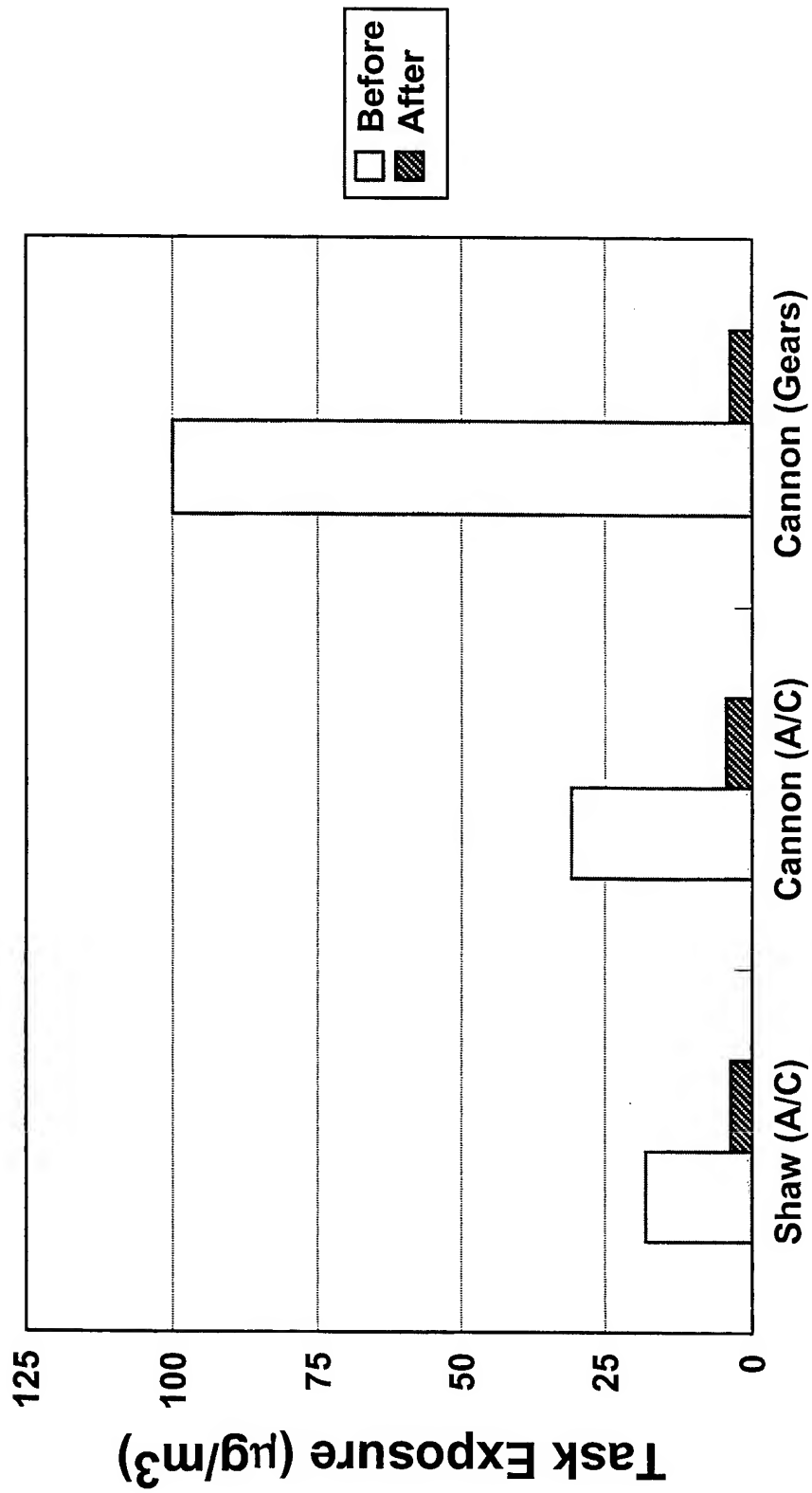
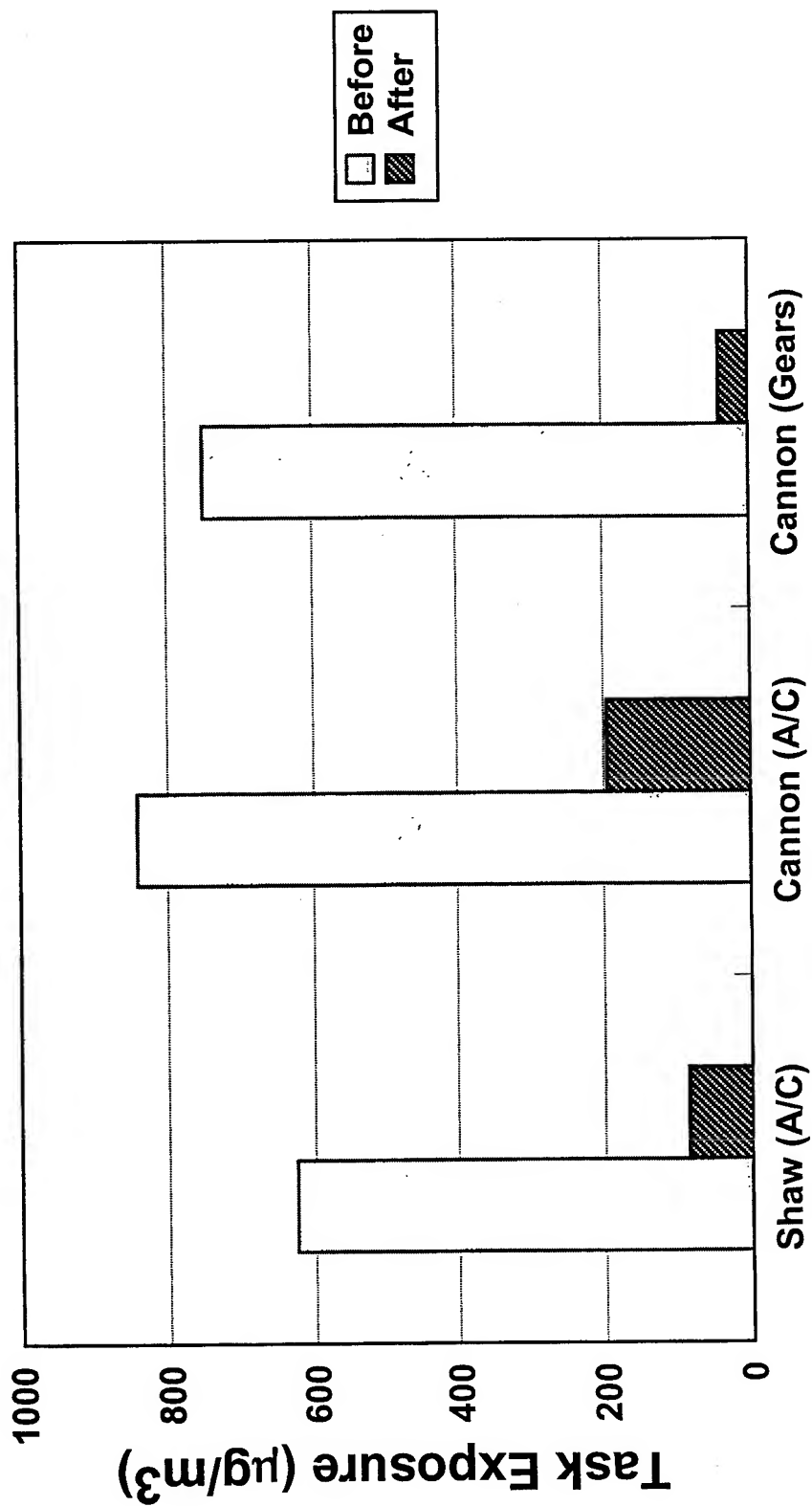


Figure B-2. Comparison of Chromate Exposures Before and After Modified Priming Procedures



Miscellaneous Factors: Routinely evaluate aircraft painting inserts or other hangar ventilation systems. Ensure painting facilities remain under negative pressure and exhaust fans and make-up air systems operate properly. Control the spread of contaminated dusts by removing contaminated coveralls before exiting work areas and designating separate break room areas.

APPENDIX C - COMPARISON OF IOM SAMPLER AND 37-MM CASSETTE

Study Design

A comparison study of the IOM sampler and 37-mm cassettes (modified by drilling a 15-mm hole in the cap), was done at Tinker AFB. Side-by-side samples were collected during the scuff sanding of a B-1 aircraft. A special holder was designed to hold the IOM and cassette adjacent to each other in the worker's breathing zone. Sampler location on the holder was randomized to minimize position bias. 25-mm PVC filters (5.0- μ m pore size) were placed in the IOM sampler cassettes prior to sampling; the cassettes were weighed with a 1.0- μ m sensitivity balance. 37-mm PVC filters (5.0- μ m pore size) were weighed in the balance, then placed in 37-mm cassettes. Workers were sampled at 2.0 lpm for the length of the sanding task, which normally lasted from one break to the next (typically about 2 hours). After sampling was complete, the IOM cassettes and 37-mm filters were re-weighed. Worker exposures were determined from measured weight differences (adjusted for sample blanks) and total sample volumes.

Results

After accounting for sampling error, 22 match pairs were available for comparison. A paired t-test indicates the IOM sampler concentrations were significantly higher than those for the modified 37-mm cassette ($p < 0.001$). The data is graphed in Figure C-1. The best-fit equation (setting the intercept to zero) is:

$$\text{IOM (mg/m}^3\text{)} = 1.92 * \text{Modified 37-mm Cassette (mg/m}^3\text{)}, r^2 = 0.75 \quad (\text{C-1})$$

The results indicate that the IOM sampler, on average, collected nearly twice the mass that deposited on the 37-mm filter. This conversion factor is similar to those documented in the professional literature [23,38]. Assuming equal aspiration efficiencies for the IOM and 37-mm cassette (both had 15-mm openings sampled at 2.0 lpm), half the mass collected by the 37-mm cassette deposited on the walls of the cassette. Similar results are expected for spray priming procedures, as inhalable particulates contribute most of the mass exposure during both sanding and priming.

Figure C-1. Comparison of Modified 37-mm Cassettes and IOM Sampler

